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# Recent Progress on Anomalous X-ray Pulsars

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**Abstract** I review recent observational progress on Anomalous X-ray Pulsars, with an emphasis on timing, variability, and spectra. Highlighted results include the recent timing and flux stabilization of the notoriously unstable AXP 1E 1048.1–5937, the remarkable glitches seen in two AXPs, the newly recognized variety of AXP variability types, including outbursts, bursts, flares, and pulse profile changes, as well as recent discoveries regarding AXP spectra, including their surprising hard X-ray and far-infrared emission, as well as the pulsed radio emission seen in one source. Much has been learned about these enigmatic objects over the past few years, with the pace of discoveries remaining steady. However additional work on both observational and theoretical fronts is needed before we have a comprehensive understanding of AXPs and their place in the zoo of manifestations of young neutron stars.

**Keywords** pulsars · magnetars · variability · X-ray spectra · timing

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## 1 Introduction

Although very few in number, the seven, and possibly nine, known so-called “Anomalous X-ray Pulsars” (AXPs; see Table 1) are potentially very powerful for making progress on the physics of neutron stars. AXPs embody properties that are highly reminiscent of two other, very different classes of neutron star: the spectacular Soft Gamma Repeaters (SGRs; see contributions by S. Mereghetti and others in this volume), and conventional radio pulsars. The great similarity of AXPs to SGRs is what makes the case for AXPs being magnetars so compelling and also offers the hope of constraining

magnetar physics. The intriguing similarities with radio pulsars offer the promise of solving long-standing problems in our theoretical understanding of the latter.

In this review, I describe the most recent observational progress on AXPs. The review will be divided into sections on timing (§2), variability (§3), and spectra (§4), choices that, unfortunately, may exhibit some personal bias, necessary given the limited space available. I hope to show that recent AXP progress has been significant, however ultimately much observational and theoretical work remains to be done before a complete picture of AXPs and their place in the neutron-star zoo becomes clear.

Note that the most comprehensive and recent review of AXPs and magnetars in general is that by Woods & Thompson (2004). In this review, I make use of the detailed, online summary of magnetar properties and references maintained at McGill University by C. Tam ([www.physics.mcgill.ca/~pulsar/magnetar/main.html](http://www.physics.mcgill.ca/~pulsar/magnetar/main.html)).

## 2 Timing

Timing observations of AXPs hold considerable information about both their surroundings via the external torques they feel, as well as potentially about their internal structure, via the “glitches” they experience. Here we summarize what is known regarding AXP timing properties, highlighting the most interesting issues.

### 2.1 Stability and Phase-Coherent Timing

Studies of the timing properties of AXPs can reasonably be categorized as pre- and post-Rossi X-ray Timing Explorer (RXTE), launched in late 1995. Prior to RXTE, timing studies were limited to occasional observations spread over many years. These characterized the overall spin-down behavior of several AXPs, and also suggested some interesting deviations from simple spin-down (e.g. Baykal & Swank 1996; Corbet & Mihara

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**Table 1** Properties of Known and Candidate AXPs.

Name	$P$ (s)	$\dot{P}^a$ ( $\times 10^{-11}$ )	$B$ ( $\times 10^{14}$ G)	Timing <sup>b</sup> Properties	X-ray Variability <sup>c</sup> Properties	Waveband <sup>d</sup> Detections	Association
CXOU J010043.1–721134	8.02	1.9	3.9	S?	S	X O?	SMC
4U 0142+61	8.69	0.2	1.3	S G?	M P	H X O I	...
1E 1048.1–5937	6.45	2.7	4.2	N	S F F B	H X I?	...
CXOU J164710.2–455216	10.61	...	...	...	...	X	Westerlund 1
1RXS J170849.0–400910	11.00	1.9	4.7	S G G	S	H X I	...
XTE J1810–197	5.54	0.5	1.7	N	O B	X I R	...
1E 1841–045	11.78	4.2	7.1	N	S	H X I?	SNR Kes 73
AX J1845–0258	6.97	...	...	...	O	X	SNR G29.6+0.1
1E 2259+586	6.98	0.048	0.59	S G	S O B P	H X I	SNR CTB 109

<sup>a</sup>Long-term average value.

<sup>b</sup>S=stable (i.e. can be phase-connected over many-month intervals, generally); N=noisy (i.e. generally difficult to phase-connect over many-month intervals); G= one glitch.

<sup>c</sup>S=stable (i.e. no variability, generally); M=modest variability; F=one flare; O=one outburst; B=bursts; P=pulse profile changes.

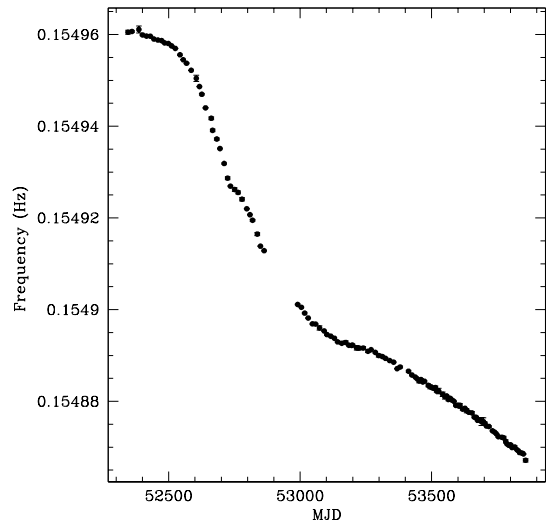
<sup>d</sup>H=hard X-ray; X=X-ray; O=optical; I=infrared; R=radio.

1997; Baykal et al. 2000; Paul et al. 2000). However the nature of these deviations could not be determined, because of the paucity of observations. Careful searches for Doppler shifts of the observed periodicities had been done (e.g. Iwasawa et al. 1992; Baykal & Swank 1996); typical upper limits on  $a \sin i$  were  $\sim 0.1$  lt-sec for a variety of orbital periods.

RXTE and its Proportional Counter Array (PCA) revolutionized the timing of AXPs. The first PCA studies of AXPs reduced the limits on  $a \sin i$  to 0.03 lt-s for 1E 2259+586 and 0.06 lt-s for 1E 1048.1–5937, effectively ruling out any main-sequence star companion and rendering binary accretion models highly problematic (Mereghetti et al. 1998).

Subsequently, a program of regular monthly monitoring of the AXPs with the PCA on RXTE was approved and showed that fully phase-coherent timing of AXPs could be done over periods of years, assuming spin-down models consisting of very few parameters (Kaspi et al. 1999). For example, Gavriil & Kaspi (2002) showed that in 4.5 yr of RXTE monitoring, pulse times of arrival for 1E 2259+586 could be predicted to within 1% of the pulse period using  $\nu$ ,  $\dot{\nu}$  and  $\ddot{\nu}$  only. Such stability is comparable to that of conventional young radio pulsars and very much unlike the large amplitude torque noise commonly seen in accreting neutron stars. Long-term, regular monthly (or even bi-monthly) observations of AXPs continue today, with four of the five persistent confirmed Galactic sources (4U 0142+61, 1RXS J170849.0–400910, 1E 1841–045 and 1E 2259+586) generally exhibiting stability that allows phase coherence with few parameters over years (Kaspi et al. 2000; Gavriil & Kaspi 2002; Gotthelf et al. 2002; Kaspi & Gavriil 2003; Dib et al. 2006).

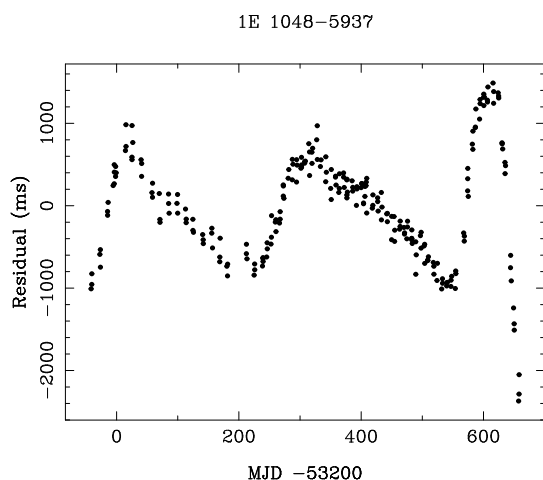
A summary of the timing properties of the known AXPs is given in Table 1.



**Fig. 1** Spin-frequency history of 1E 1048.1–5937 from RXTE monitoring (work in preparation). Note the simple spin down in the last 1.9 yr.

One of the established persistent Galactic AXPs, 1E 1048.1–5937, has been much less stable than the others, such that phase-coherent timing with unambiguous pulse counting over more than a few weeks or months has been difficult to achieve (Kaspi et al. 2001; Gavriil & Kaspi 2004). This poor stability is apparent in the source's

frequency evolution (Fig. 1). Recently, however, during an extended period of pulsed flux stability following two long-lived X-ray flares (see §3.3 below), the timing has also become quite stable, such that unambiguous phase coherence could be maintained over a nearly 2-yr interval from MJD 53158 to 53858 using 4 spin parameters, although significant residuals remain (Fig. 2). Details of these results will be described elsewhere. It remains to be seen if an end to this stability will be accompanied by additional radiative events, a result that would hopefully be useful for strongly constraining models for the torque noise and flares.

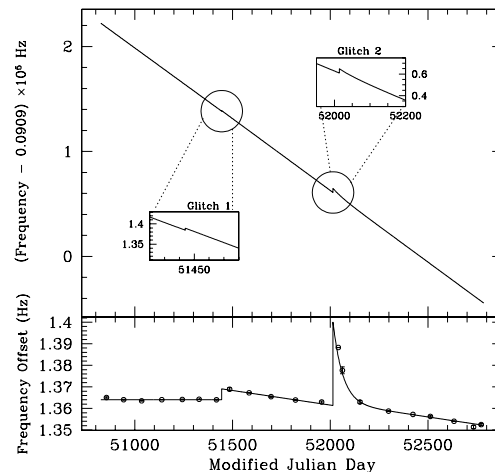


**Fig. 2** Phase residuals following removal of four frequency derivatives for the last 1.9 yr of data for AXP 1E 1048.1–5937. The features are roughly 300 d apart and are presently consistent with being due to random timing noise (work in preparation).

## 2.2 Glitches

The impressive timing stability seen in most AXPs, in which pulse periods could easily be determined to better than a part in a billion, permitted for the first time the unambiguous detection of sudden spin-up glitches in AXPs. 1RXS J170849.0–400910 was the first pulsar seen to glitch (Kaspi et al. 2000). This glitch had a fractional frequency increase of  $6 \times 10^{-7}$ , very similar to what is seen for the Vela pulsar and other comparably young objects. Continued monitoring of the same AXP revealed a second, larger glitch 1.5 yr later (Kaspi & Gavril 2003; Dall’Osso et al. 2003), with a nearly complete recovery of the frequency jump, unusual by pulsar standards (see Fig. 3).

In June 2002, at the time of a major radiative outburst (see §3 below), the otherwise stable AXP 1E 2259+586 exhibited a large glitch (fractional frequency increase of  $4 \times 10^{-6}$ ) which was accompanied by significant and truly remarkable recovery in which roughly



**Fig. 3** Long-term RXTE timing data for 1RXS J170849.0–400910 showing the two glitches observed thus far (from Kaspi & Gavril 2003).

a quarter of the frequency jump relaxed on a  $\sim 40$ -day scale. As part of that recovery, the measured spin-down rate of the pulsar was temporarily larger than the long-term pre-burst average by a factor of 2! This recovery was somewhat similar to, though better sampled than, the second glitch seen in 1RXS J170849.0–400910. The 1E 2259+586 event was the first (and still the only unambiguous, but see §3.3) time a spin-up glitch in a neutron star was accompanied by any form of radiative change. This event suggests that large glitches in AXPs are generally associated with radiative events; perhaps such an event occurred at the time of the second glitch in 1RXS J170849.0–400910 but went unnoticed due to sparse monitoring. The very interesting recoveries of the 1E 2259+586 and second 1RXS J170849.1–400910 glitches seem likely to be telling us something interesting about the interior of a magnetar and how it is different from that of a conventional, low-field neutron star. This seems worth more attention than it has received in the literature thus far.

Recently a timing anomaly was reported in AXP 4U 0142+61 (Dib et al. 2006). Although at first the anomaly seemed consistent with a spin-up glitch following a burst observed on April 6, 2006 (Kaspi et al. 2006), the subsequent data do not support a simple glitch interpretation. This is work in progress and will be reported on elsewhere. However, Morii et al. (2005) and Dib et al. (2006) suggest that this pulsar may have glitched during a large observing gap in 1998–99, a possibility supported by apparent changes in the pulse profile that seem to have occurred in the same interval (Dib et al. 2006).

### 3 AXP Variability

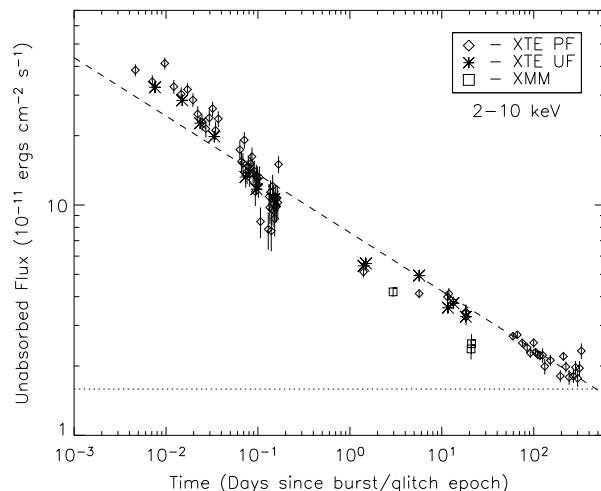
Arguably one of the most interesting recent discoveries in the study of AXPs is the range and diversity of their X-ray variability properties. Pre-RXTE, there was variability reported (e.g. Baykal & Swank 1996; Corbet & Mihara 1997; Oosterbroek et al. 1998; Paul et al. 2000), however those relatively sparse observations were made using different instruments aboard different observatories, some imaging, some not, and were often presented without uncertainties, making their interpretation difficult. Moreover, given the sparseness of the observations, identifying a time scale for the variations, or being certain the full dynamic range was being sampled, was not possible.

Post-RXTE, and, additionally, with contemporaneous observations made using Chandra and XMM, the picture has become much clearer. Presently there appear to be at least four types of X-ray variability in AXP pulsed and persistent emission: outbursts (sudden large increases in the pulsed and persistent flux, accompanied by bursts and other radiative and timing anomalies, which decay on time scales of weeks or months), bursts (sudden events, lasting milliseconds to seconds), long-term flux changes (time scales of years), and pulse profile changes (on time scales of days to years). We examine each of these phenomena in turn.

#### 3.1 Outbursts and Transients

The current best example of an AXP outburst is that seen in June 2002 from 1E 2259+586 (Kaspi et al. 2003; Woods et al. 2004). This outburst, which lasted only a few hours, fortuitously occurred during a few-hour monthly RXTE monitoring observation. During the outburst, the pulsed and persistent fluxes increased by a factor of  $\sim 20$  (see Fig. 4), there were over 80 short SGR-like bursts in a few-hour period (see §3.2), there were substantial pulse profile changes (see §3.4 below), there was a short-term decrease in the pulsed fraction, the spectrum hardened dramatically, there was a large glitch (see §2.2 above), and there was an infrared enhancement (see §3.5). All this came after over 4 yr of otherwise uneventful behavior (Gavril & Kaspi 2002). Note that had RXTE not been observing the source during the outburst, the entire event would have appeared, from the monitoring data, to consist principally of a glitch. With only monthly monitoring, all but the longest-term radiative changes would have been missed. Interestingly, this outburst was notably different from SGR outbursts; for the AXP, the energy in the outburst “afterglow” ( $\sim 10^{41}$  erg; see Fig. 4) greatly exceeded that in the bursts ( $\sim 10^{37}$  erg). This is in direct contrast to the giant flares of SGRs. The reason for this difference is unknown.

The outburst of 1E 2259+586 seems likely to be a good model for the behavior of the “transient” AXP XTE J1810–197. This source, unknown prior to 2003,



**Fig. 4** Flux time series plotted logarithmically following the 2002 1E 2259+586 outburst (Woods et al. 2004). Diamonds denote inferred unabsorbed flux values calculated from RXTE PCA pulsed-flux measurements. Asterisks and squares mark independent phase-averaged unabsorbed flux values from RXTE and XMM, respectively. The dotted line denotes the flux level measured using XMM 1 fortuitously week prior to the glitch. The dashed line is a power-law fit to the PCA flux measurements during the observations containing the burst activity ( $<1$  day).

was discovered as a bright 5.5 s X-ray pulsar, upon emerging from behind the Sun in that year (Ibrahim et al. 2004), and has been fading ever since. The source’s spin down and spectrum are consistent with it being an AXP. Gotthelf et al. (2004) showed from archival ROSAT observations that in the past, the source, in quiescence, was nearly two orders of magnitude fainter than in outburst. See the contribution by Gotthelf et al. in this volume for more details. An important question raised by the discovery of XTE J1810–917 is how many more such objects exist in our Galaxy? This has important implications for AXP birthrates.

Such an outburst may also explain the behavior of the unconfirmed transient AXP AX J1845–0258 (see Table 1). Pulsations with a period of 7 s were observed in an archival 1993 ASCA observation (Torii et al. 1998; Gotthelf & Vasisht 1998), however subsequent observations of the target revealed a large drop in flux, and pulsations have not been redetected. Although no  $\dot{\nu}$  has been measured for this source, it seems likely to be an AXP given its period and location at the center of a supernova remnant (Gaensler et al. 1999). It thus is plausible that the 1993 outburst was similar to that of 1E 2259+586 or XTE J1810–197, although the likely dynamic range for this source is unprecedented for an AXP. See the contribution to these proceedings by Tam et al. and Tam et al. (2006) for more details.

One of the most puzzling aspects of transient AXPs is why the quiescent source is so faint. In the standard mag-

netar model, the requisite magnetic field decay energy input is persistent, as is the magnetospheric twist for a fixed magnetar-strength magnetic field (Thompson & Duncan 1996; Thompson et al. 2002). Although much attention has been paid to why a magnetar’s flux might skyrocket suddenly – a sudden reconfiguration of the surface following a crustal yield – relatively little attention has been paid to how to stop or hide the bright X-ray emission from a neutron star presumably harboring a magnetar-strength field.

### 3.2 Bursts

During the 2002 1E 2259+586 outburst, over 80 short, SGR-like X-ray bursts were seen superimposed on the overall flux trend over the course of the few-hour RXTE observation (Kaspi et al. 2003). Some were super-Eddington, though only on very short (few ms) time scales. In a detailed analysis of these bursts, Gavriil et al. (2004) found that in most respects, they are identical to SGR bursts. Specifically, the durations, differential fluence distribution, the burst morphologies, the wait-time distribution, and the correlation between fluence and duration, are all SGR-like. However a few of the burst properties were different from those of SGR bursts: for example, the AXP bursts had a wider range of durations, the AXP bursts were on average less energetic than in SGRs, and the more energetic AXP bursts have the hardest spectra – the opposite of what is seen for SGRs. Unlike in SGRs, the AXP bursts were correlated with pulsed intensity.

Bursts in AXPs were first reported by Gavriil et al. (2002) who discovered two such events in archival RXTE data from the direction of 1E 1048.1–5937. A third burst, found nearly 3 yr later (Gavriil et al. 2006), unambiguously identified the AXP as the origin thanks to a simultaneous pulsed flux increase. The bursting behavior in this source is not obviously correlated with any other property, although we note tentatively that no bursting has been seen during the most recent 2 yr, when the pulsar has been exhibiting much improved timing (see §2, Fig. 1) and also pulsed flux stability. Perhaps the bursting was symptomatic of whatever activity also caused the timing instability and pulsed flux flares (see §3.3 below).

Four bursts have also been seen from the transient AXP XTE J1810–197 (Woods et al. 2005). These events consisted of a  $\sim 1$  s spike followed by an extended tail in which the pulsed flux was enhanced, similar to the third burst of 1E 1048.1–5937 and a handful from 1E 2259+586. The XTE J1810–197 and 1E 1048.1–5937 bursts also showed a correlation with pulsed intensity, as did some of the 1E 2259+586 bursts.

These observations led Woods et al. (2005) to hypothesize that there are in fact two distinct classes of bursts, which they named Type A and B. Type A bursts are similar to SGR bursts, in that they are uncorrelated

with pulse phase and have no extended tails. Type B bursts, on the other hand, thus far observed exclusively in AXPs, are correlated with pulsed intensity, generally have long extended tails, and those tails tend to contain more energy than the burst itself. As both types of burst were seen in 1E 2259+586, clearly they are not mutually exclusive, even during the same event. Woods et al. (2005) speculate that Type A bursts have a magnetospheric trigger, whereas Type B bursts originate from crust fractures.

Most recently, a total of five small, sub-Eddington X-ray bursts have been seen between April and June 2006 from 4U 0142+61 (Kaspi et al. 2006; Dib et al. 2006, work in preparation). The latter four, all within a single RXTE orbit, were clearly accompanied by a pulsed flux increase (by a factor of  $\sim 4$  relative to the long-term average) which decayed on a time scale of minutes. This suggests, as does the accompanying pulse profile change and timing anomaly, that this source may have entered an extended active phase.

With at least half of the known AXPs now established as capable of bursting, it is clear that the production of occasional though clustered short SGR-like bursts is a generic AXP phenomenon.

### 3.3 Long-Term Flux Variations

Variability in AXP 1E 1048.1–5937 had been reported for years (e.g. Corbet & Mihara 1997; Oosterbroek et al. 1998; Baykal et al. 2000; Mereghetti et al. 2004). RXTE monitoring determined the time scale of the changes and the morphology of the pulsed light curve with far superior time sampling than in previous studies (Gavriil & Kaspi 2004). Specifically, the RXTE monitoring showed that over  $\sim 7$  yr, the source exhibited two extended pulsed flux “flares,” the first lasting  $\sim 100$  days and the second lasting over a year, each with rise times of several weeks. Assuming a distance to the source of 5 kpc (which is not especially well established), Gavriil & Kaspi (2004) estimated the total energy released in the pulsed components of the first and second flares to be 3 and  $30 \times 10^{40}$  erg, respectively. Subsequently, Tiengo et al. (2005), using XMM, which (unlike RXTE) is sensitive to pulsed fraction, showed that in fact the pulsed fraction is anticorrelated with the phase-averaged flux, suggesting the total energy released was at least twice that in the pulsed component.

During these flares, the spin-down rate fluctuated by at least a factor of 10 (Gavriil & Kaspi 2004). However, there was no obvious correlation between the detailed evolution of the spin-down rate and flux. Recently, while its flux has been stable, 1E 1048.1–5937 has shown much greater timing stability (see §2 above). This suggests that the large torque noise and flux flaring were causally related; we must await another such event to confirm this.

The flaring observed in 1E 1048.1–5937, a new phenomenon not yet observed in any other AXP, is well un-

derstood in the context of the twisted magnetosphere model (Thompson et al. 2002). The flux enhancements can be seen as being due to increased twisting of the magnetosphere by currents originating from the stressed crust. If so, a harder spectrum is expected when the pulsar is brighter. Unfortunately the existing data cannot confirm this important prediction for this source. Decoupling of the torque from the pulsed flux can occur in this model depending on the location of the enhanced magnetospheric current; a current near the pole will have a disproportionate impact on the spin-down. Gavril & Kaspi (2004) argued that the absence of predicted torque–luminosity variations in this source are problematic for models in which the X-ray emission originates from accretion from a fossil disk (e.g. Chatterjee et al. 2000; Alpar 2001, but see Ü. Ertan et al.’s contribution).

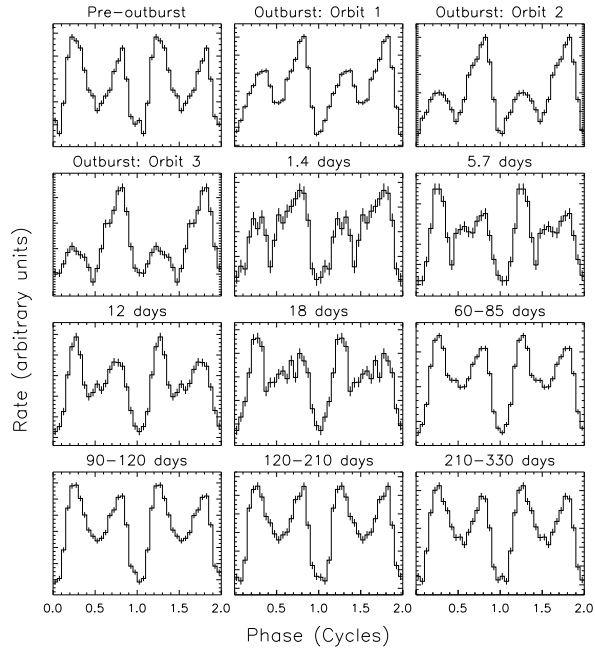
The twisted magnetosphere model prediction that flux should be correlated with hardness, though unconfirmed in 1E 1048.1–5937, does seem to be borne out in observations of 1RXS J170849.0–400910 (Rea et al. 2005, see contribution by N. Rea et al., this volume). Moreover, those authors suggest that the epochs of greatest hardness occur near those in which glitches were detected in this source (see §2.2), with subsequent softening post-glitch. At least one additional glitch needs to occur, with better observational coverage, before this conclusion is firm.

Recently, much longer-term radiative variations have been identified in AXP 4U 0142+61, in which the pulsed flux appears to be increasing steadily since 2000, such that there was a  $\sim 20\%$  change by early 2006, just prior to its exhibiting a sudden pulse profile change and bursts. Interestingly, this variation does not seem consistent with magnetospheric changes given the predictions of the twisted magnetosphere model. This behavior is described in more detail in the contribution by R. Dib et al. to this volume as well as in Dib et al. (2006). One particularly interesting implication of the increase in X-ray flux from this source is that the phenomenon provides a simple test of the irradiated fall-back disk model for the near-IR emission (see §4.3). If the source of irradiation, the AXP, increases in brightness, the disk ought to as well.

### 3.4 Pulse Profile Changes

The first observed pulse profile change in an AXP was reported by Iwasawa et al. (1992) using *GINGA* data obtained in 1989. They witnessed a large change in the ratio of the amplitudes of the two peaks in the pulse profile of 1E 2259+586, namely from near unity to over two. They also reported a contemporaneous timing anomaly which, in hindsight, is consistent with a spin-up glitch.

A very similar pulse profile change was witnessed during and immediately following the 2002 outburst of 1E 2259+586 (Kaspi et al. 2003; Woods et al. 2004). Here, the ratio of the amplitudes of the two pulses in the pro-



**Fig. 5** Pulse profile changes in 1E 2259+586 following its 2002 outburst (Woods et al. 2004).

file went from unity pre-outburst to roughly two mid-outburst, relaxing back to normal on a time scale of a few weeks (Fig. 5). Curiously, the temporarily larger peak in the 2002 outburst appeared to be the temporarily smaller peak in 1989, suggesting that even if the physical origin of the events is the same, the details of the geometry were different. Given the nature of this event, a likely explanation for the pulse profile change is a magnetospheric reconfiguration following a crustal fracture that simultaneously affected the inside and outside of the star. This very strongly suggests that the Iwasawa et al. (1992) pulse profile change was observed not long after a similar event; this is consistent with their reported timing anomaly, and suggests such events occur roughly every 1-2 decades in this source.

Most recently, long-term (i.e. time scale of several years) pulse profile variations have been reported for AXP 4U 0142+61 (Dib et al. 2006, see contribution by R. Dib et al, these proceedings). These accompany a long-term pulsed flux increase (see §3.3). The profile changes are consistent with a significant event having occurred some time between mid-1998 and 2000, in which the second and higher harmonics of the profile increased dramatically, and have been returning to their pre-event level ever since. This gradual evolution was, however, interrupted by an apparent sudden activity episode, in which an SGR-like burst was detected along with a timing anomaly in April 2006 (see §3.2; Kaspi et al. 2006). The analysis of the latter data are in progress.

### 3.5 Near-IR Variability

The large number of recent near-IR detections of AXPs has revealed an interesting new variability phenomenon in these sources. Following the 2002 outburst of 1E 2259+586, there was an infrared ( $K_s$ ) enhancement by a factor of  $\sim 3$ , 3 days post-outburst. This then decayed together with the X-ray pulsed flux, with identical power-law indices (see Fig. 4; §3.1 Tam et al. 2004). Those authors concluded that the origins of both flux increases were magnetospheric (but see contribution by Ü. Ertan, these proceedings Ertan et al. 2006, for the fossil-disk viewpoint). A similar correlation was also reported for AXP XTE J1810–197 (Rea et al. 2004).

Meanwhile, significant near-IR variability has also been reported for AXP 1E 1048.1–5937 (Israel et al. 2002; Wang & Chakrabarty 2002; Durant & van Kerkwijk 2005). However, if anything, the near-IR is *anti-correlated* with the X-ray flux. This is puzzling given the 1E 2259+586 and XTE J1810–197 results. It is worth keeping in mind, however, that there is now some evidence that 1E 1048.1–5937 has been in an active phase from which it may have recently emerged (see §2); it will be interesting to see how its near-IR flux varies now that both the X-ray flux and timing have stabilized (see Fig. 1).

In addition, Durant & van Kerkwijk (2006a) report on near-IR observations of 4U 0142+61 and report no apparent correlation with the X-ray pulsed flux. They argue that the situation for this source is unclear and warrants additional, more frequent observations. Simultaneous far-IR observations would also be of interest to establish conclusively that they originate from a separate mechanism, namely radiation from a passive, irradiated fall-back disk (Wang et al. 2006).

## 4 AXP Spectra

The description of spectra of AXPs has, until very recently, been limited to the soft (0.5–10 keV) X-ray band, as that is where AXPs were discovered and have been traditionally studied. However the recent discoveries of optical and near-IR emission have cast them firmly into the multi-wavelength regime, and the even more recent detections in the hard X-ray band as well as in the far-IR and radio bands broadens the situation even further.

### 4.1 X-ray Spectra

In the traditional 0.5–10 keV X-ray band, AXPs have long been known to show two-component spectra, which are well described by a blackbody plus a power law (e.g. White et al. 1996; Israel et al. 2001; Morii et al. 2003). It is currently thought that the blackbody arises from internal heating due to the decaying intense magnetic

field, while the non-thermal component is a result of resonant scattering of the thermal seed photons off magnetospheric currents in the twisted magnetosphere (Thompson et al. 2002). Detailed spectral modelling in this framework appears to describe the spectrum of 1E 1048.1–5937 (Lyutikov & Gavril 2006), but see the contribution by N. Rea in these proceedings. Although some attempts were made to model the entire spectrum using a single blackbody distorted by the effects of the intense magnetic field on the atmosphere (e.g. Özel 2001), these could not reproduce the non-thermal component adequately (e.g. Perna et al. 2001; Thompson et al. 2002; Lai & Ho 2003).

There is evidence supporting a physical connection between the two components, such as the very slow evolution of the pulse profile with energy (e.g. Israel et al. 2001; Gavril & Kaspi 2002). For some AXPs (for example 1E 1048.1–5937 and 1E 1841–045), there is little if any variation in the pulse profile, with no obvious difference between profiles in energy bands that are thermally and non-thermally dominated. Even in other AXPs for which the profile is energy-dependent, the profiles in bands that are thermally and non-thermally dominated are still very similar. This is in stark contrast to the situation for rotation-powered pulsars, for which the thermal and non-thermal components generally have radically different X-ray pulse profiles (e.g. Harding et al. 2002).

Recently, Halpern & Gotthelf (2005) have suggested on purely theoretical grounds that the spectrum of XTE J1810–197 is more appropriately described by a two-component model consisting of two blackbodies (see also contribution by E. Gotthelf et al. in this volume). Their main argument for this interpretation is that an extrapolation of the power-law component to low energies greatly exceeds that expected if the seeds are thermal photons from the surface, as the blackbody eventually runs out of photons to supply. Moreover, they argue, the expected blackbody cutoff would then result in a substantial underestimate of the infrared flux, assuming the latter is part of the non-thermal spectrum. Very recently, Durant & van Kerkwijk (2006c) have shown using independently measured interstellar column densities that the intrinsic spectra really are cut off, i.e. the power-law component does not in fact extend far below the observable band. If correct, the rationale for preferring the double blackbody over the blackbody plus power law would not apply.

This section would not be complete without some discussion of the interesting recent results of Durant & van Kerkwijk (2006b,c), some of which are reported on by Durant et al. in this volume. Specifically, using high-resolution X-ray spectroscopy, they identified absorption edges whose amplitudes determine  $N_H$  under reasonable assumptions, independent of the overall continuum spectral modelling. Using these newly measured values of  $N_H$  and a novel distance estimation technique using reddening runs with distance for red clump stars, they were able to first im-

prove the spectral fits for several AXPs significantly, and second determine much improved distance estimates for them. Amazingly, among other things, they find that the soft X-ray luminosities of practically *all* AXPs are consistent with the value  $\sim 1.3 \times 10^{35} \text{ erg s}^{-1}$ . Durant & van Kerkwijk (2006b) argue that this is consistent with the magnetar model's prediction that there should be a saturation luminosity above which internal neutrino cooling is at work.

#### 4.2 Hard X-ray Spectra

A particularly interesting recent AXP discovery is that they are copious hard X-ray emitters (Molkov et al. 2004; Kuiper et al. 2004). Though their spectra in  $\nu F_\nu$  appear to fall off in the softer X-ray band, they turn up again above  $\sim 10 \text{ keV}$ . The luminosities above  $10 \text{ keV}$  independently greatly exceed the available spin-down power by factors of over 100. This requires a new mechanism for accelerating particles in the magnetosphere, in addition to an energy source, presumably the decaying magnetic field. SGR 1806–20 has also been detected in this energy range, though interestingly it is somewhat softer than the AXPs (Mereghetti et al. 2005). Kuiper et al. (2006) have further shown that the hard X-ray emission is a generic property of AXPs, and for at least three sources, extends without a break up to  $150 \text{ keV}$ . They also show from *COMPTEL* upper limits that the break must lie under  $\sim 750 \text{ keV}$ . Determining the location of the break could greatly constrain emission models, possibly even providing independent evidence for the magnetar-strength field. See the contribution by P. den Hartog et al. in this volume for details regarding hard-X-ray emission from 4U 0142+61.

This hard X-ray emission, apart for being interesting for constraining the physics of magnetars, offers a unique way of detecting AXPs throughout the Galaxy, since the soft X-ray emission suffers from high absorption, especially in the inner Galaxy. A focussing hard X-ray instrument (like the NASA mission concept *NuSTAR*) would have the capability of detecting every magnetar in the Galaxy, provided their hard X-ray emission is generic, even in quiescence.

#### 4.3 Optical and Infrared Spectra

Currently, five of the known AXPs have been conclusively detected in the near-IR, with only 4U 0142+61 (the closest, least absorbed AXP) having been detected optically. None of the SGRs has been detected optically, and only one has been seen in the near-IR (SGR 1806–20; Kosugi et al. 2005), and only during a particularly active phase. For a summary of these detections, see [www.physics.mcgill.ca/~pulsar/magnetar/main.html](http://www.physics.mcgill.ca/~pulsar/magnetar/main.html) and references therein.

The near-IR spectra of AXPs are an interesting puzzle. First, given the variability in the near-IR (§3.5), piecing together an accurate instantaneous spectrum using photometry requires contemporaneous observations, not always possible. Even more of a problem has been the generally unknown reddening toward the sources, which have an enormous impact on the inferred intrinsic spectrum. Nevertheless, some information regarding the optical and near-IR spectra of AXPs is known. Overall, the major mystery is how the optical and near-IR emission connects with the X-ray spectrum. The blackbody emission seen in X-rays grossly underpredicts that in optical/near-IR, while a simple extrapolation of the non-thermal component (when the spectrum is described in this way – see §4.1) generally overpredicts it. Expecting at least the optical emission to connect spectrally with the X-rays is reasonable given that the latter is pulsed in 4U 0142+61 (Kern & Martin 2002; Dhillon et al. 2005) hence seems likely to originate in the magnetosphere, as does, presumably, the non-thermal X-ray emission.

Very recently, Wang et al. (2006) have shown using *Spitzer* data of 4U 0142+61 that in the far-IR, there appears to be a component that is spectrally distinct from the near-IR emission. They interpret this component as resulting from a passive debris disk irradiated by the central X-ray source. They suggest that such disks, which originate from matter that falls back following the supernova explosion, may be ubiquitous around neutron stars. They further suggest that the correlated near-IR/X-ray flux decay observed by Tam et al. (2004) following the 2002 outburst of 1E 2259+586 and for XTE J1810–197 (see §3.5) could be a result of a disk around that AXP as well, a possibility also discussed by Ertan et al. (2006) and Ü. Ertan et al. in these proceedings. If the fallback-disk interpretation is correct for 4U 0142+61, the pulsed X-ray flux change recently detected in this source (§3.3) may provide an opportunity for a test of the disk hypothesis (Dib et al. 2006, and R. Dib et al. in this volume), as there should be a correlated increase in the near-IR flux. This idea requires that the overall X-ray flux, not just the pulsed component, also be increasing, which requires observations with an imaging X-ray telescope to verify.

#### 4.4 Radio Spectrum

Very recently (in fact *after* this meeting took place!), Camilo et al. (2006) reported the detection of radio pulsations from XTE J1810–197. This was a magnetar first and in many ways a welcome discovery, having provided a nice radiative link between magnetars and radio pulsars, in addition to the similarity already established from timing observations (see §2). It also demonstrated that pulsed radio emission can definitely be produced in magnetar-strength fields in contrast to some predictions (e.g. Baring & Harding 1998). Previous searches of other non-transient AXPs had come up empty (e.g.



Burgay et al. 2006; Crawford et al. 2006, and see contribution by M. Burgay et al., this volume), suggesting the radio emission here might somehow be related to this source's transient nature. Given the small radio beaming fraction reasonably expected for such slow pulsars, the absence of radio pulsations from other sources could also be due to small-number statistics.

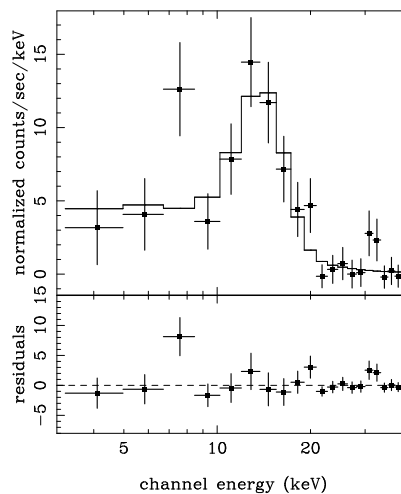
Also interesting is the unusual spectrum of the radio emission seen from XTE J1810–197. It has an unusually flat spectrum, with spectral index  $> -0.5$ , whereas radio pulsars have very steep spectra, with most indices between  $-1$  and  $-3$ . XTE J1810–197 is the brightest radio pulsar known at frequencies  $>20$  GHz. Why this should be the case is an interesting new puzzle for magnetar physics, one which has the potential to shed crucial new light on the long-standing problem of the origin of radio emission in rotation-powered pulsars.

#### 4.5 Spectral Features

Finally, there have been reports of features in AXP spectra. The first such report was for 1E 1048.1–5937 during the first of its two observed 2001 bursts (Gavril et al. 2002). The feature, which was most prominent in the first 1-s of the burst, was extremely broad and seen apparently in emission at a central energy of 14 keV (see Fig. 6). In terms of flux, it was comparable to the burst continuum emission. It was very significant; Monte Carlo simulations showed that such a feature at any energy would be seen only 0.01% of the time. Gavril et al. (2006) saw a similar feature in the third observed 1E 1048.1–5937 burst. In that case, the central energy measured was also  $\sim 13$  keV. In addition, Woods et al. (2005) observed a similar feature in one burst from XTE J1810–197, this time at energy 12.6 keV, with probability of chance occurrence  $4 \times 10^{-6}$ . If interpreted as proton cyclotron lines, the energies of these features imply a magnetic field above  $\sim 10^{14}$  G, consistent with the magnetar hypothesis. However if the features are interpreted as electron cyclotron lines, the implied field is correspondingly  $\sim 2000$  times lower. The latter would not necessarily be inconsistent with the magnetar interpretation, as it is unclear what altitude above the neutron-star surface these lines originate.

Note that similar spectral features during SGR bursts have also been reported in the tails of a few SGR bursts (Ibrahim et al. 2002, 2003, see contribution by A. Ibrahim et al., these proceedings). However, recently their statistical significance has been questioned (see contribution by P. Woods et al.).

Rea et al. (2005) reported spectral features at certain rotational phases from 1RXS 170849.0–400910 from *BeppoSax* data. These were claimed at the time to be significant at the  $\sim 4\sigma$  level. Observations with XMM of the same source saw no such features, implying either that the *BeppoSax* features were spurious or that the effect is



**Fig. 6** Spectrum of the 1 s after the peak of the first burst observed from 1E 1048.1–5937 (Gavril et al. 2002).

time variable. See the contribution by N. Rea et al. in these proceedings for more information.

#### 5 Conclusions

My hope in writing this review is to demonstrate that there remain many important unsolved problems in the study of AXPs. Overall, the basic issue of what differentiates AXPs from SGRs remains, as does the origin of the intense magnetic fields inferred. Other important issues for which there simply was not enough space for discussion here include the possible association of AXPs (and SGRs) with massive star progenitors (e.g. Figer et al. 2006; Munro et al. 2006, see contribution by B. Gaensler et al.), the puzzling lack of “anomalously” bright X-ray emission from high-magnetic field radio pulsars (see contribution by M. Gonzalez et al.), and the proposed connection between magnetars and the so-called “RRATS” (McLaughlin et al. 2006, and see contribution by A. Lyne in this volume).

As for how some of these problems will be solved, continued monitoring observations with RXTE, as well as targeted studies with Chandra, XMM and INTEGRAL, will obviously be of use. Greater concerted efforts in the optical and near- and far-IR are warranted, as are careful and repeated radio searches for transient pulsations or other phenomena. Finally, target-of-opportunity observations at the times of the rare moments of AXP activity are definitely crucial for unravelling the overall physical picture of these very interesting sources.

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